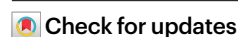


Towards scenario representation of adaptive capacity for global climate change assessments

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Climate change adaptation needs, as well as the capacity to adapt, are unequally distributed around the world. Global models that assess the impacts of climate change and policy options to reduce them most often do not elaborately represent adaptation. When they do, they rarely account for heterogeneity in societies' adaptive capacities and their temporal dynamics. Here we propose ways to quantify adaptive capacity within the framework of Shared Socioeconomic Pathways, a scenario set widely used by climate impact and integrated assessment models. A large set of indicators spanning different socioeconomic dimensions can be used to assess adaptive capacity and deliver adaptation-relevant, scenario-resolved information that is crucial for more realistic assessment of whether and how climate risks can be reduced by adaptation.

Adaptation—the process of adjustment to the actual or expected climate and its effects¹—is an integral element of the response to the risks posed by climate change. Research on various aspects of adaptation has been growing substantially over the past decade^{2–4}, and its urgency has been elevated in international, national and local policy agendas. However, both the needs for adaptation and the capacities to adapt are unevenly distributed around the world^{5,6}. The brunt of impacts is projected to burden countries of the Global South, which generally experience the highest challenges to adaptation and limitations in adaptive capacity⁷.

State-of-the-art global modelling tools that deliver key information on different sectoral impacts (for example, in agriculture, water, human health and economic damages) and the policy options to deal with the consequences of climate change do not elaborately represent adaptation, and even less so the heterogeneity in capacity to adapt^{8–12}. This could lead to underestimation of the actual risks by being too optimistic about the level of adaptation that can be implemented.

Global models in climate change research typically explore a range of different socioeconomic futures using quantified narratives called Shared Socioeconomic Pathways (SSPs), which are conceptualized to reflect societal challenges to mitigation and adaptation¹³. Even though more than half of SSP-based publications are on impacts, adaptation and vulnerability, only about 3% of the studies focus specifically on adaptation^{14,15}. This in part highlights that a common understanding of what constitutes 'socioeconomic challenges to adaptation' remains elusive even among the research community using the SSPs.

In this Perspective, we propose ways to advance towards a more robust integration of adaptation in global models. We first provide a brief overview of how adaptation is conventionally represented in the modelling tools. Here we do not address regional or local models that specialize in modelling adaptation or participatory integrated assessments that tend to be more advanced in their representation of adaptation^{8,16,17}; we instead focus on global climate impact models (CIMs) and integrated assessment models (IAMs; both process-based and

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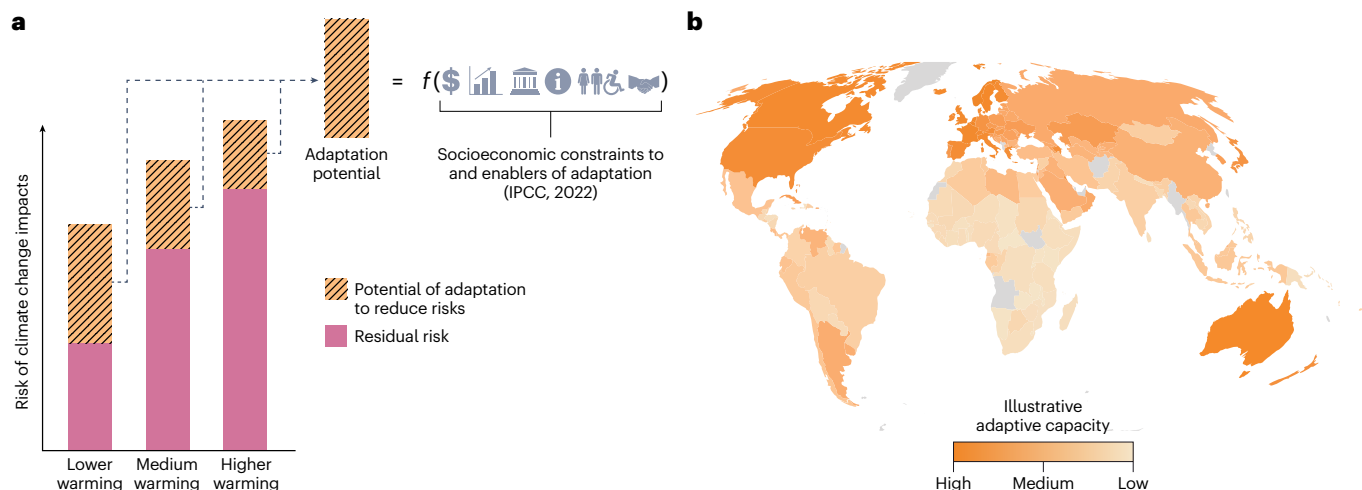


Fig. 1 | Typical characterization of the risk of climate change impacts versus socioeconomic characterization of adaptive capacity. **a**, Adaptation potential in current global risk assessments varies with levels of warming, with adaptation effectiveness expected to decrease at higher degrees of warming^{24,86}. Adaptation potential, however, is also a function of socioeconomic constraints or enablers (finance, economy, institutions, information, human capital and

sociocultural characteristics) of adaptation, which affect the potential of adaptation at each level of warming. **b**, Illustrative example of the globally unequal distribution of country-level adaptive capacity based on the cooling gap study⁵⁴. Panel **b** adapted with permission from ref. 38 under a Creative Commons license CC BY 4.0.

cost–benefit types). Second, we propose coupling the existing strands of research on adaptation constraints, enablers, adaptive capacity and SSPs to provide scenario-resolved quantification of adaptive capacity. We also provide a step-by-step example of how adaptive capacity could be assessed on a sectoral level. Third, we present an outlook for model integration and the implications for assessing climate change risk, as well as future research avenues, particularly those relevant for global assessments used by the IPCC. The approach suggested here can accelerate ongoing efforts to improve representation of adaptation and help in accounting for inequalities in adaptive capacity, which would enable more precise impact estimates and more reliable policy advice when weighting different strategies to deal with climate change.

Conventional representation of adaptation in global models

Global CIMS and IAMs differ in their primary objectives: while CIMS assess ways in which biophysical hazards will impact human and other ecosystems, IAMs look for solutions to climate change, traditionally focusing primarily on mitigation. Both types of models need improvements in their representation of adaptation¹². In the context of CIMS, adaptation can reduce exposure and vulnerability to climate hazards and therefore reduce impacts. Adaptation can be defined a priori and projected over time. In IAMs, decisions on how to adapt and how to mitigate are weighted against each other—options that synergize with the model objectives (for example, minimize cost given constraints on emissions and damages) will be chosen over those that do not (for example, (mal)adaptation options that are expensive and emissions intensive).

Adaptation is notoriously complex to model and is often represented in stylized ways¹⁸. In global CIMS, it is typically modelled as autonomous (as opposed to planned) adaptation by undefined actors, which happens, for example, in response to a change in demand or is triggered by a mitigation policy^{19,20}. Furthermore, not incorporating the differential ability between countries (or other units of analysis) to deploy adaptation means that adaptation is sometimes modelled in binary terms as full (or optimal—where costs equal benefits) adaptation versus no adaptation, which misses the range of possibilities in between that are shaped by socioeconomic contexts. Expecting (optimal) adaptation might not be realistic, because adaptation depends on a

range of socioeconomic factors that might be suboptimal. Similarly, a society might not be within the ‘adaptation frontier’, which defines the space between a system’s safe and unsafe operating spaces²¹. Such approaches to modelling also neglect more advanced dynamic adaptation planning that enables flexible responses to challenges over time²². Some models do impose constraints on adaptation implementation, but they are most often time-invariant⁸, even though it is questionable whether current or historical socioeconomic conditions would be effective for addressing climate change in the future. As such, current assumptions underlying ways in which adaptation is modelled, which take it for granted that it can or will happen wherever and whenever it is needed, are probably overly optimistic^{8,10}.

Summaries of global climate change impact assessments therefore do not treat adaptation in a nuanced way. Landmark syntheses of climate change science by the IPCC contain figures where adaptation reduces a portion of the future risk of climate change that depends on future levels of warming, but the level of adaptation potential is either static or only varies in effectiveness at different levels of warming. This does not reflect the embeddedness of adaptation in the socioeconomic context that is recognized elsewhere in reports, especially in relation to the assessments of constraints to and enablers of adaptation (Fig. 1)^{23–25}.

Assumptions about adaptation are consequential further down in the modelling chain—namely, for representation of impacts and modelling economic damage functions in process-based IAMs²⁶, but also for possible standalone integration of adaptation as a policy option in IAMs that might create synergies or trade-offs with mitigation. In all cases, approaches to account for adaptation in process-based IAMs are still in early stages. Cost–benefit IAMs, as the other dominant class of IAMs, more often integrate adaptation when using economic optimization techniques to assess costs and benefits of climate policy. These approaches could be problematic for several reasons: there may be difficulties in aggregating costs of adaptation, aggregating non-economic costs and benefits, and incorporating justice elements in adaptation decision-making, and models could be overly optimistic about the net benefits of adaptation if no constraints are accounted for in modelled adaptation^{12,27}. Model outputs from cost–benefit IAMs based on these assumptions could lead to conclusions that adaptation can substitute mitigation and have been widely criticized^{28,29}.

Adaptive capacity as a measure of adaptation potential

Several different factors affect the ability of actors to adapt, some in a way that constrains adaptation and some that help enable it³⁰. While concrete adaptation projects are usually implemented locally, the conditions for enabling or constraining adaptation play out across all levels of decision-making, and contextual factors at national or societal levels can shape the adaptive capacity on the ground. Conceptualizing adaptive capacity in this way is similar to the capability approach of Nussbaum and Sen³¹, who argue that societal challenges such as overcoming poverty can be tackled through increasing individuals' financial, political and other socioeconomic capabilities. The capabilities do not prescribe the individual actions that Nussbaum and Sen call 'functionings' but span the option space available to an individual.

In the context of climate change adaptation, adaptive capacity resembles Nussbaum and Sen's understanding of capabilities (for example, financial means, human capital and strong institutions), in that it provides agency to a local actor to pursue (or not) a desired adaptation action. As is the case in welfare economics and theories of justice, in which the capability approach was developed, it does not seem practical or generalizable to speculate about the actions of individual actors as they are eventually based on value judgements in a highly specific context. However, the socioeconomic factors underlying adaptive capacity are quantifiable in a much more generalizable fashion and can be assessed, described and, as we will show, projected in line with mainstream scenarios of socioeconomic development.

Due to the complexity and contextuality of adaptation at multiple spatial scales and the various boundary conditions that affect it, there is no universal agreement on the relationship between these multiple enabling and constraining factors, including their relationship to adaptive capacity. For this reason, finding a basis on which to compare adaptive capacity between societies and what its implications are for the impacts of climate change is challenging. Different conceptualizations and quantifications of adaptive capacity exist in the literature, often presented as composite indicators of various underlying socioeconomic and sometimes environmental dimensions^{32–35}. Existing approaches typically vary in the scale at which they are applied (such as local³⁶, regional³⁷ and global³⁸) and the exact proxy indicators they are considering, but they are similar in the higher-order socioeconomic dimensions used to capture adaptive capacity, such as economic and financial capital, human capital and institutions^{39,40}.

The Sixth Assessment Report of the IPCC frames governance (legislation, regulation, institutions and litigation), finance (needs, sources, intermediaries, instruments, flows and equity) and knowledge (climate services, big data, indigenous/local knowledge, co-production and boundary organizations) as the enabling conditions that "enhance the feasibility of adaptation (and mitigation) options". The Sixth Assessment Report also synthesizes evidence on constraints that "make it harder to plan and implement adaptation action" and notes that "the ability of actors to overcome these socioeconomic constraints largely influences whether additional adaptation is able to be implemented"^{7,41}. Similarly to the higher-order socioeconomic dimensions that can be identified in the literature, these constraints are categorized in six groups: economic (for example, economic mobility and the sectoral structure of the economy), social/cultural (for example, social justice concerns, attitudes and values), human capacity (for example, education, training and skills), governance/institutions/policy (for example, laws, regulations and government effectiveness), financial (for example, access to resources) and information/awareness/technology constraints. For representing the key determinants of adaptation dynamics in global models, we consider a range of socioeconomic factors that constrain or enable adaptation potential under the umbrella of adaptive capacity, defined as "the ability of systems, institutions, humans

or other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences"¹⁴.

Projections of adaptive capacity

We propose that adaptive capacity can be represented within the framework of the SSPs, a set of five scenarios designed for exploring a range of future pathways of socioeconomic development^{13,42}. SSPs are used, on the one hand, to derive future emission trajectories, which are then translated into temperature increases and biophysical hazards; and, on the other, to estimate the impacts of climate change by combining the future climate with, for example, future population or economic assets exposed to climate hazards. They are advanced in the representation of a multitude of mitigation pathways and their implications for meeting (or missing) a temperature target. But they can also be used to define and explore boundary conditions for decision-making on adaptation. For example, in scenarios with high inequality, a model could explore the implications of adaptation occurring only in wealthy parts of the world or help understand socioeconomic requirements for a more equitable global distribution.

Within the SSP framework, various indicators were developed as part of the original scenario set (demographic and gross domestic product (GDP) indicators) and as later extensions (additional quantifications of SSP-relevant dimensions that emerged in the literature), both of which are listed in Table 1.

Projections of adaptive capacity spanning economic, human resources and environmental dimensions have been done in the context of vulnerability assessments aligned with the Special Report on Emissions Scenarios used in previous climate change assessments^{43,44}. Advances have also been made in understanding vulnerability within the SSP context, particularly with respect to health risks⁴⁵. However, no attempt has been made so far to comprehensively quantify the future development of adaptive capacity alongside the SSPs, even though adaptation challenges and mitigation challenges are the two axes of the framework. Global CIMs and IAMs that operate with the SSPs should generally be able to absorb scenario-resolved information about adaptive capacity¹⁵.

The data listed in Table 1 are all global (country-level) datasets, typically including the historical period on whose basis the modelling was made, followed by projections along the five SSP scenarios. Each is described in more detail in the Supplementary Information. The dimensions quantified as part of the original SSPs listed in Table 1 are GDP, population, education and urbanization, while the rest of the indicators have emerged from subsequent publications. They are suitable for scenario-based assessments of adaptive capacity because of their broad coverage of relevant dimensions and their internal consistency with the underlying SSP narratives, meaning that indicators can be combined with each other while following the properties of the same qualitative storyline. Neither all indicators nor all dimensions of adaptive capacity proposed here will be relevant for every research question seeking to identify socioeconomic dimensions of adaptive capacity. Future users are thus encouraged to draw on theory and previous literature before screening for the potentially relevant indicators and before deploying a statistical technique to gain a robust understanding of the key drivers.

Table 1 is not meant to be exhaustive but rather a first stocktake of the currently available quantified dimensions of adaptive capacity that are consistent with the IPCC syntheses. Aside from keeping track of the new relevant developments and updating the database, further advances of this research agenda would benefit from establishing a community exchange that involves, for example, scenario designers and users and creators of adaptation-relevant data, with the aim of facilitating further development and verification of indicators and model intercomparison. A new generation of scenarios for a wide use in climate change research would ideally explicitly focus on advancing the quantification of adaptive capacity, with possible endogenization of

Table 1 | Global datasets of quantitative indicators developed as part of the original SSP scenario framework or as subsequent independent extensions, and their corresponding publications

Dimension	Indicator	Publication(s)
Economic/ financial  	GDP per capita	Refs. 71–74
	Structural change	Ref. 75
	Extreme poverty	Ref. 76
	Income inequality	Ref. 77
	Urbanization	Refs. 78,79
Governance/ institutions 	Remittances	Ref. 80
	Governance	Ref. 81
	Government effectiveness	Ref. 81
	Control of corruption	Ref. 81
Human capacity / information  	Rule of law and civil liberties	Ref. 82
	Population size	Ref. 83
	Age structure	Ref. 83
	Educational attainment	Ref. 83
	Mean years of schooling	Ref. 83
	Human Development Index	Ref. 84
Social/cultural 	Migration flows	Ref. 80
	Gender Inequality Index	Ref. 85
	Gender gap in mean years of schooling	Ref. 83

dimensions such as governance, conflict or gender equality that affect multiple other aspects of socioeconomic development.

Examples of quantifications of adaptive capacity

Two recent studies assessed adaptive capacity within the SSP framework for air conditioning³⁸ and sustainable irrigation⁴⁶. The first option helps adapt to climate-related heat stress, and the latter is critical to responding to water stress in agriculture. Conceptually, both studies explore the critical gap between the theoretical maximum and the actual or expected level of adaptation that occurs, due to the limited adaptation capacity at different stages of socioeconomic development. Figure 2 illustrates a stepwise approach based on the concept of the “cooling gap”^{38,47}.

The steps consist of (1) identifying the adaptation gap (for example, the difference between the current level of uptake of an adaptation option and its theoretical maximum), (2) utilizing statistical models (for example, regression analysis) to analyse the socioeconomic factors that can explain the gap either between countries or within a country over time and (3) deriving pathways of the future adaptation gap using the projections of the socioeconomic drivers within the SSP scenario framework. When the first step is not possible because the data are unavailable or because the adaptation option has not yet been used at scale or at all, stakeholder and expert elicitation or analogies to existing practices and technologies could be used instead to identify the socioeconomic indicators relevant for a certain adaptation option.

With a similar approach, the change in the irrigation gap in a cross-country regression analysis has been estimated⁴⁶. The study found governance to be a relevant barrier, implying ultimately that additional calories could be produced if governance was improved to enable faster and more widespread implementation of sustainable irrigation. These insights can be operationalized in, for example, agricultural crop models to constrain (or enable) the uptake of irrigation technologies on the basis of a country’s level of governance.

The conceptualization of adaptive capacity within the SSPs presented here can be used flexibly to assess socioeconomic factors that might render the previously assumed level of adaptation (for example, full or optimal) unattainable and can be applied to different geographical or sectoral levels of interest. Additional adaptation options could be assessed following the example in Fig. 2, for different sectors and regions, to advance towards more comprehensive cross-sectoral assessments of adaptation, recognizing that this is not always straightforward due to a lack of consistent data on existing sectoral measures across scales and time. A different but complementary approach would be to assess adaptive capacity on the country level on the basis of insights from literature reviews or from the IPCC syntheses of evidence. This could be expanded with subnational data to explore variation in adaptive capacity within countries and corroborate insights from case studies, especially from large countries. For both examples given, the next steps in IAM integration could be to analyse synergies and trade-offs between mitigation and adaptation pathways by comparing energy requirements for the implementation of adaptation linked to scenario-dependent assumptions of adaptive capacity, and mitigation targets that need to be achieved. Fossil-fuel-powered air conditioning would result in a trade-off with the need to reduce emissions, while thermal insulation as a measure against heat stress would be synergetic in that it simultaneously reduces emissions and provides an adaptation option.

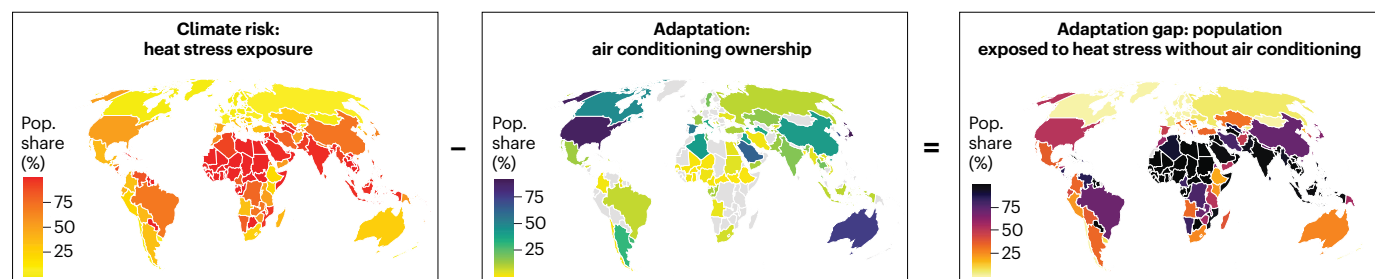
Advances towards model integration

The quantification of adaptive capacity within the SSP framework would allow for a quantitative assessment of the potential of adaptation that varies between countries, between scenarios and over time. This would constitute a crucial step towards a more elaborate integration of adaptation in CIMS that assess the effects of climate change on societies and ecosystems. Additionally, it can facilitate the incorporation of biophysical impacts and economic damage functions in IAMs and expand the options to reduce climate risk through both mitigation and adaptation strategies (Fig. 3).

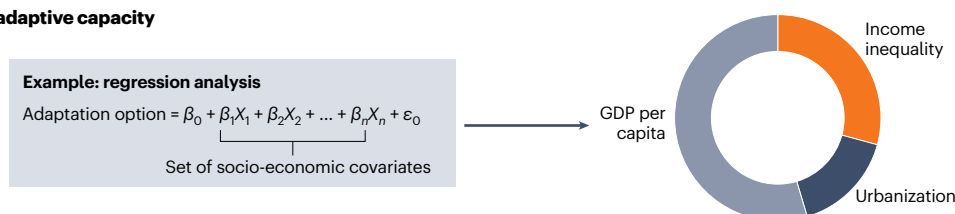
CIMS can use scenario-specific and time-varying adaptive capacity to parameterize adaptation-relevant inputs⁸. The exact model input that should be linked to adaptive capacity is specific to each model. Technologies meant to improve crop yields, policies meant to manage water allocation or finance for building dams are some of the examples of model inputs that can be, with sufficient theoretical grounding, linked to the various socioeconomic factors presented in Table 1 and then replaced as scenario-resolved model input. For the earlier example of irrigation, the literature suggests that it depends on the quality of governance and the absence of corruption, which can be corrosive for externally financed irrigation development projects^{46,48}. This means that a global agricultural impact model may consider relating the level of irrigation not only to finance but also to governance characteristics of the area in which it is expected to be implemented.

In the context of IAMs, adaptive capacity will play an important part in the integration of climate impacts into mitigation scenarios. Without adaptation pathways, modelling of impacts and the estimation of damages or the required level of mitigation to reduce risks could be misleading. Additionally, the more recent generation of IAMs are modelling access to different types of basic services, particularly in the domain of economic and human capacity. Access to services can be increased by investing in infrastructure provisions such as electricity, decent housing, sanitation, clean drinking water, transport and telecoms²⁴ as well as investments in societal structures that support attaining human well-being^{49,50}. Access to services that constitute the requirements for ‘decent living’ and are also codified in the Sustainable Development Goals has many synergistic benefits for reducing vulnerability and raising living standards⁵¹. Because such services are strongly related to the components of adaptive capacity and expand what was previously captured mostly by GDP, IAMs are

a Identification of the adaptation gap



b Identification of adaptive capacity



c Projections of the adaptation gap (RCP4.5 and five SSPs)

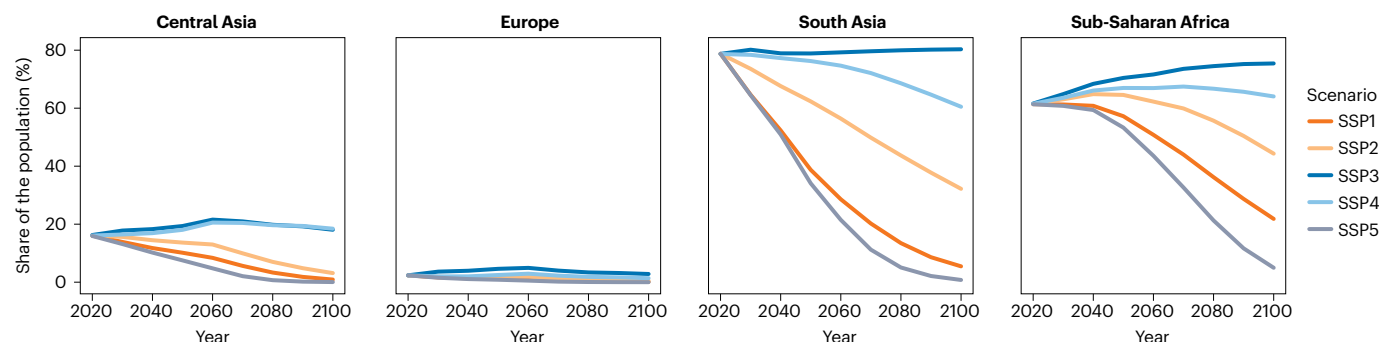


Fig. 2 | Stepwise approach to assessing adaptive capacity. **a**, The adaptation gap (cooling gap) is expressed as the difference between the population potentially exposed to heat stress and the actual population with access to air conditioning. Note that all values here are calculated on the country level (population-weighted for heat stress exposure), which probably masks within-country inequality in all aspects of analysis. The maps are based on values for 2018. **b**, Uptake of air conditioning is found to be a function of GDP per capita, income inequality and urbanization, which can be projected alongside the SSPs and used to derive future rates of air conditioning on the basis of the socioeconomic conditions. This was estimated using a panel data regression,

which allows for assigning different weights to the relevant components of adaptive capacity and is based on previously found theoretical relationships⁸⁷. **c**, Projections of air conditioning access can be coupled with future heat stress projections (here in Representative Concentration Pathway (RCP) 4.5) to estimate the cooling gap in the future: the results vary between a residual risk of 2 billion people with heat stress globally in the best-case scenario of socioeconomic development (SSP1) and 5.2 billion people in a scenario of stagnant development (SSP3) in 2050. Panels **a** and **c** adapted with permission from ref. 38 under a Creative Commons license CC BY 4.0.

now better equipped to dynamically model resource requirements for increasing adaptive capacity. Mitigation scenarios in IAMs can then be complemented with varying levels of sectoral and societal adaptation that account for different trajectories of adaptive capacity, which would improve the understanding of synergies and trade-offs between mitigation and adaptation. Also, a set of indicators that reflect historical and future trajectories of access to these basic services would enhance climate risk assessment, better quantify the potential for risk reduction and help identify residual risk, across sectors, by region and by demographics^{52–55}.

Avenues for further research

Further methodological and conceptual refinements will help solidify the assessments of adaptive capacity for a widespread and more comparable use in models. Efforts to improve data availability and the empirical identification of determinants of adaptative capacity, regardless of

its spatial level or scale, are one priority area for further development. A particular emphasis should be on using machine-learning-assisted approaches that integrate remote sensing techniques and robust econometric models to improve the realism and internal consistency of the projections. For situations where data are not available or are patchy (which pose difficulties both for robust statistical assessments and for downscaling of scenarios to lower geographical levels), the emergence of citizen science data validation, big data and harmonization of data sources could ameliorate some of these obstacles in the future^{56–58}. Additionally, systematic reviews could help further expand the evidence base on drivers of adaptive capacity^{2,52}. Probabilistic methods such as Bayesian model averaging that provide posterior probability distributions for conditional forecasts based on ensembles of models, rather than point estimates from unique statistical specifications, could help in addressing problems of model uncertainty and time-varying impacts^{59–61}. Additionally, methods that exploit discontinuities at

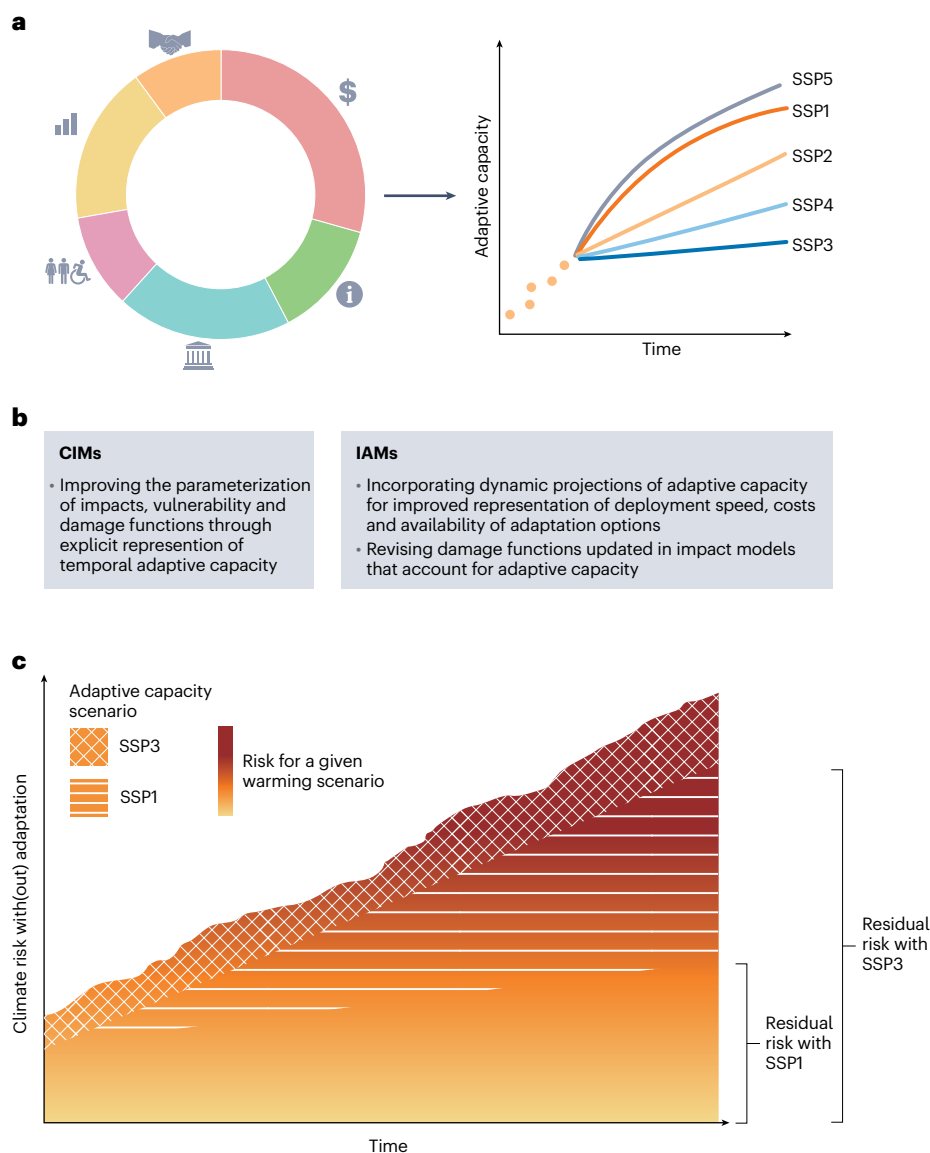


Fig. 3 | Conceptual connections between adaptive capacity, model integration and risk assessments. **a**, Quantified adaptive capacity (see Table 1 for details on the different possible dimensions), which can be projected along the five SSPs ready to be implemented in CIMs and IAMs. **b**, Possible entry points for the operationalization of adaptive capacity in CIMs and IAMs. **c**, Resulting

implications for assessments of climate risk (here shown in one hypothetical warming scenario with low mitigation) and residual risk that depends on the level of adaptive capacity (shown in the diverging scenarios SSP1 (fast socioeconomic development) and SSP3 (stagnant development)).

(national) borders can be useful to deal with endogeneity affecting socioeconomic variables and instead infer causal effects, in this case among socioeconomic drivers of adaptation⁶².

A second promising avenue is downscaling to spatial scales that would increase relevance for adaptation decision-making. However, using scenarios on a finer geographical scale (for example, for subnational or local levels) needs to be done with caution. SSPs in this case can be regarded as the “boundary conditions”⁶³ that provide a general context in which more specific, locally relevant assumptions can still be embedded, even if not explicitly modelled by more macro-level assessments. Adaptive capacity is likely to be affected by the interactions between the micro and macro levels, but assessments of these interaction processes are scarce⁵⁴. It is therefore important to also assess how various existing indicators of adaptive capacity are consistent across scales and contexts³⁹. Accounting for within-country inequalities would be one way to ensure that country-level indicators are representative of the subnational picture too. A bottom-up construction of adaptive

capacity with indicators relevant for the household level, for instance, would allow for a spatially more granular assessment of vulnerability to climate risks while offering the possibility to examine multiscale interactions. A study of heterogeneity in the adaptive response to environmental shocks at the micro level can inform macro-level modelling efforts and refine projections, to the extent that the relevant factors are represented within the scenario framework, by incorporating differential effects depending on the characteristics of the individuals affected.

Another challenge for the coherence of policy-relevant information derived from model estimates concerns the (lack of) model representation of cross-sectoral impacts and adaptation needs. Risk assessments traditionally follow linear hazard–exposure–risk pathways but often ignore interlinkages between sectors that would otherwise amplify or reduce the final climate impact and the needs for adaptation, particularly for the food–water–energy nexus^{55,63}. Multi-sectoral IAMs (at national and global scales) are well placed to analyse cross-sectoral impacts and drivers of adaptive capacity, which

should to the extent possible try to capture dimensions relevant for all connected sectors and understand the potential trade-offs and synergies between adaptation and mitigation options, while avoiding pitfalls of siloed sectoral decision-making.

We want to highlight two general considerations related to the use of scenarios that need to be kept in mind when developing pathways of future adaptive capacity. The first one pertains to the issue of uncertainty. While scenarios can be viewed as tools to communicate a range of possibilities and “insights rather than numbers”^{64,65}, uncertainty analyses can help ensure that the underlying assumptions are consistent. They not only make policy-relevant outputs robust to uncertainty but also help identify the strongest levers for action. For example, a structured uncertainty analysis, whereby a family of extensions (including regional and local applications of the scenario framework) were associated with each basic scenario, could help expand the deterministic results and define the range around each reference scenario⁵³. Systematic analyses of the impacts of model structure and uncertainty around the model inputs on the final output have also been done in a probabilistic Monte Carlo framework, where repeated simulations are performed with randomly sampled parameters from predefined probability distributions, which can be a way to help decision makers test whether deterministic estimates hold over a relevant range⁴⁴.

The second issue relates to a limiting aspect of quantifying adaptive capacity within the SSP scenario framework. By design, none of the original scenarios represent deteriorations in socioeconomic development or sudden shocks to the system such as climate extremes, economic crises or conflicts⁶⁶. While fragmentation, limited international cooperation and stagnant economic growth are features of the worst-case scenario (SSP3), the scenarios otherwise do not explore fast deteriorations or societal collapse because of conflict or other reasons. This means that the projections of adaptive capacity that adhere to the storylines of the original SSP framework will inherit a degree of scenario optimism from the original set of scenarios, which could be better addressed by the risk-based and uncertainty-based approaches mentioned above.

A concrete example can be given for climate-related disasters, where financial constraints present in developing and least developed countries can result in negative feedback loops whereby adaptive capacity is increasingly undermined by rising hazards, further decreasing risk reduction potential at higher levels of warming²⁴. The possibility of societal tipping points being reached due to a breakdown of adaptive capacity cannot be excluded. Constraining likely levels of adaptive capacity by way of expert elicitation can be one way of reflecting such possible interactions in estimates of future adaptation potential and residual risks (O. Serdeczny, manuscript in preparation).

Similarly, social and political unrest related to armed conflict leads to socioeconomic deterioration in terms of human capacity and lower economic growth, which in turn hinders both adaptation and mitigation action⁶⁷. Advances in scenario conceptualization that would account for shocks, disruptions and multiple intersecting crises (for example, war, food security, pandemics and climate extremes) would also be necessary to fully capture the socioeconomic complexity and would allow for an identification of regions and populations whose need for increased adaptive capacity is the most pressing, because they are the most vulnerable and exposed to compound and cascading risks due to poverty, lack of access to basic services, political instability or governance challenges²⁴. Recent advances in probabilistic projections of conflicts^{66,68} pave the way to accounting for disruptions such as wars in scenarios, which would also allow for the re-estimation of indicators of adaptive capacity and offer a way to endogenize complex interactions in the CIM and IAM frameworks.

Discussion

The potential of adaptation to reduce climate risk in modelling tools needs to be considered in relation to its socioeconomic context. This Perspective offers an approach for quantitative assessments of global

inequalities in the capacity to adapt to climate change as part of SSPs, which should enable global CIMs and IAMs to better constrain their assumptions, produce more realistic and more elaborate assessments of the consequences of climate change for human and other systems, and provide more comprehensive policy advice.

We acknowledge that methodological developments would further advance our proposition, especially in the phase of identifying relevant dimensions of adaptive capacity as well as in the characterization of uncertainties. Issues that cannot necessarily be resolved in this approach are situations where adaptation is constrained by factors that cannot easily be captured with quantitative indicators⁴¹. Entrenched patterns of inequality and marginalization linked to gender, ethnicity, socioeconomic status and citizenship that have resulted in some groups being more vulnerable to climate impacts with lower capacities to adapt are examples of interactions that will also be absent from the quantifications proposed here^{24,69}.

Even being able to perfectly capture all relevant explanatory factors of adaptive capacity might not suffice in a comprehensive analysis of adaptation, as high levels of adaptive capacity do not automatically mean that adaptation action will take place or that it will be effective once implemented. However, in a manner analogous to the capability approach, increased adaptive capacity should expand the opportunity space or potential for adaptation to occur. Further research is needed to establish the exact mobilizing mechanisms that will serve as triggers for converting adaptive capacity into adaptation implementation⁷⁰. For example, the implementation of adaptation in one region can be analysed in a case study fashion to understand what generalizable factors were necessary for this to happen. However, this can arguably be done only in hindsight and is therefore not possible for adaptation that is meant to respond to future challenges. Instead, we can rely on projections of the conditions that make it more or less likely.

The next steps in scenario development would need to involve devising a verification process, whereby new quantifications (which are not part of the original set) that are in line with the SSPs could be officially associated with the scenario set. Such a process would at minimum require transparent and replicable data and code, as well as expert elicitation of the consistency with the underlying narratives. Additional community efforts would involve a public review, scenario vetting and intercomparison exercises when more than one indicator is available (as is the case for GDP projections, for example). Furthermore, the scientific community that is designing and using scenarios for climate change research needs to ensure that this space includes a diverse set of actors, particularly experts from countries of the Global South, for which the relevance of such scenarios will be especially high given the disproportionate impacts they are and will continue to be facing.

Insights into the possible trajectories of socioeconomic conditions are, of course, not limited to better understanding of climate change adaptation and its model implementation but are at the core of a broader sustainable development agenda. The constraints to adaptation are simultaneously constraints to poverty eradication and widespread provision of education and health care, for example, which cannot be taken for granted for large fractions of the global population.

Scenario-resolved indicators of adaptive capacity can help improve our understanding of its global heterogeneity and temporal dynamics. Model operationalization would add an additional layer to the identification of hotspots where high exposure to climate-related hazards overlaps with low adaptive capacity. Most importantly, accounting for adaptive capacity in modelling tools would reduce the possibility of overstating the potential of adaptation or understating the urgency and magnitude of mitigation that must remain the priority for climate risk reduction.

Data availability

The data listed in Table 1 are available in a certified repository⁸⁸ and are open access. The data can also be interactively accessed through the

Socio-economic and Political Data Explorer at <https://soccoexplorer.shinyapps.io/soc-ex/>.

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Author contributions

M.A. conceived the paper and created the figures with contributions from E.B. and C.-F.S. M.A., C.-F.S., J.C.C., T.L., R.M., K.R., E.T., A.T. and N.v.M. contributed to writing the paper. M.A. wrote the revisions with inputs from E.B. and C.-F.S.

Competing interests

The authors declare no competing interests.

Additional information

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